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Mini Review

Magnitude assessment for stellarquakes

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Abstract

The extensive expansion of astrophysical investigations during the last years is a factor that needs a new approach and preparation to meet new challenges. The missions of telescopes Hubble and Web, the increased resolution of on-land telescopes, the new missions to the Sun, etc. reveal the possibility of knowing much more about the stars and star quakes. New unexpected seismic events have been detected on the Sun. From time to time Sun protuberances generate seismic waves very similar to those observed on the Earth's oceans. This similarity is remarkable and gives the possibility to use the earthquake magnitude scale to assess the magnitude of sunquakes generated by solar flares. Magnitude as a seismic measurable unit was suggested by Charles Richter and Beno Gutenberg by the analogy of stars' magnitude. The dependence of the earthquake magnitude to seismic energy and vice versa is an achievement that gives the way for the empirical transformation from magnitudes to seismic energy and vice versa. Sunquakes also contain other carried energy substances, but assuming only energy carried by the surface seismic waves it is a real possibility to perform the same approach for the assessment of sunquakes by a magnitude scale. The magnitude assessment of this research was limited only to stellarquakes – i.e. seismic events occurring on the fluid stars similar to the Sun and presented only by the surface seismic waves. As a result of our methodology stellarquakes magnitude scale was adapted using a similar approach to the Richter's magnitude. The important issue is also the assessment of the possible variance of the stellarquakes magnitude for the different types of stars.

Introduction

During the last years space seismology has been developing intensively [1] and the problem of measuring the power of extraterrestrial seismic events (Mars, Moon, etc.) raised the problem of the magnitude evaluation. Even more, the sunquakes were recorded and thus have been put into discussion, how to measure the power of seismic events observed on stars and called starquakes. As for now, there are only sunquakes registered (and some neutron star blasts as well), so efforts will be made to introduce the starquake magnitude scale. The physical base of this approach is the observed surface waves on the Sun after the powerful eruptions [2]. The analogy between the surface earthquake waves' magnitude and surface plasma waves on the Sun is the fundament of this research. On it, an attempt will be made to estimate the power of the star quakes, to compare the powerful seismic events observed on the Sun, and to extrapolate the scale to other known fluid stars and their possible starquakes.

In this paper, starquakes are named stellarquakes to underline that this definition is used for the seismic events on the fluid stars. For the first time, the stellarquake magnitude problem of other fluid stars [3] (except the Sun) is mentioned in the paper – "Sunquakes: helioseismic response to solar flares" by Alexander G. Kosovichev, 2014. In the discussion paragraph "1.4 Challenges in understanding sunquakes" of the chapter "Sunquakes: helioseismic response to solar flares" he discussed the problems of the seismic sources and responses of the photosphere to the flares of the fluid stars.

The first sunquake was observed by the SOHO mission, especially on 9th July 1996, and the first magnitude assessment was performed [2]. Following this a series of sunquakes were studied for the 24th solar cycle (2011-2017) [4], a catalogue of

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sunquakes was created [5] and statistics of occurrence and a lot of their properties were revealed [4]. As the source of sunquakes is not clearly proven there are several models trying to fit the observational data. Some explain the generation mechanism by an impact from above to the photosphere, some by eruptions from inside the Sun's interior and there are more exotic suggestions as "holography reconstruction" [6].

There is not a general approach how to assess the magnitude of the fluid stars by a common methodology of stellarquakes' magnitude estimation. We use the standard procedure for the magnitude and energy evaluation of the seismic events (earthquakes) based on the surface waves magnitude scale developed by Richter and Gurenberg during the thirties of the 20th century [7,8]. Then extrapolating the seismic energy release investigation to estimate the level of expected magnitudes of stellarquakes and eventually assess the diapason of the lower and upper boundaries and the possible variations and uncertainties. These considerations are based on simple mathematical relationships, reasonable physical assumptions, and a common methodology to evaluate the possible stellarquakes magnitudes.

Definitions

To create a consistent understanding of the terminology used in this work a short vocabulary is suggested giving the basic definitions:

Earthquakes – seismic events on the Earth

Magnitude of earthquakes – logarithmic scale created by Richter and Gutenberg to measure the power of earthquakes (for details, see next paragraph). An increase of 1 magnitude unit means an earthquake is about 32 times stronger in power [9,10].

Starquakes - seismic events (frequently called glitches) on the neutron/pulsar/magnetar/ compact stars. These stars are composed of crust and superfluid interiors [11]. A starquake is a sudden rearrangement of the crust of the star [12]. It is characterized by the destruction of the crust, generation of gravitational waves, and intensive gamma and X-ray emissions. There are in general two main seismic events on these stars – the first one is the destruction of the crust followed by star oscillations after starquakes [13,14]; and the second is the formation of elastic mountains on spinning compact stars [15]. To study the energy budget of such stars, heavy mathematics is used to obtain the realized energy and to get reasonable results and assessment of energy distribution of many different events developing during the lifetime of such stars [13]. The strongest measured star quake was recorded on December 27, 2004. It released so much energy, that if it happened on Earth; it would be equivalent to a level 32 earthquake "Richter" magnitude (i.e. assuming that this scale was used to measure the starquake) [16].

Star magnitude - is a historical unit of stellar brightness and its definition says that a change of 5 magnitudes represents a factor of 100 in intensity of brightness [17].

Sunquakes – these are seismic events characterized by the propagation of surface seismic waves generated by Sun flares [3]. Not all sun eruptions generate sunquakes (they are about 10% - 20% of all eruptions) [18].

Helioseismology - the branch of astrophysics that investigates the interior structure of the Sun by studying its surface wave oscillations. The mean period of the vibrations is about five minutes, which corresponds to a frequency of about 0.003 Hz [19].

Fluid stars – these stars are similar to the Sun. In this study, the investigation of the power (magnitude) of these surface seismic waves' events is assessed using approximation, extrapolation, and analogy with earthquake surface waves.

Stellarquakes – seismic events observed on the surface of fluid stars. For the purpose of this work, the only investigation is done considering the surface seismic waves generated by flares and possibly visible on the photosphere of fluid stars. All assessments are calibrated by the sunquakes.

Astroseismology - a part of astrophysics studying seismic events and oscillations on stars, planets, satellites, and other terrestrial and non-terrestrial space objects [19].

Mathematical fundamentals

The classical formula for earthquake magnitude determination according to Richter and Gutenberg is [9]:

$$m = \log (A/T) - f(\Delta,h) + k, \qquad (1)$$

where A is the maximum amplitude, T is the respective period of the wave, f (Δ,h) is the function depending on the distance and depth of the earthquake source, and k is the empirical calibration constant.

For surface waves, the introduced empirical formulae is [9]:

$$M_S = \log (A/T)_{max} + k \log\Delta + c, \qquad (2)$$

where A is the maximum amplitude of the surface waves on the seismogram, T is the respective period, Δ is the epicentral distance from the seismograph to the epicenter, k is the coefficient (between 1.5-1.7), and c is the constant for the calibration of the device (3.0-3.5).

Due to the sensitivity of the seismographs and their response function the large magnitudes create so-called "saturation" of the magnitude scale. To avoid this, many different types of magnitude scales were introduced (body waves, moment, surface waves, local, duration, etc. magnitudes [10]).

Much more important are the formulas for the transformation of the magnitude to the energy and vice versa. They are related to the relationships of kinetic energy E proportional to the amplitude (A^2), ($E \sim A^2$), density of the substrate, and frequency of the waves.

The combination of the energy and magnitude gives the empirical formulas for surface seismic waves to calculate the energy of earthquakes and vice-versa – from the energy to calculate the magnitude:

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$$\log E_S = 4.4 + 1.5\,Me \quad (3)$$

or

$$Me = (\log E_S - 4.4)/1.5. \quad (4)$$

where Es is the earthquake energy in Joules, and Me is called energy magnitude (this means that this magnitude is calculated using the empirical relationship Es-Me) [10].

The relationship between Joules and ergs is:

1 Joule = 10^7 ergs

Logarithmic scale means that the change of magnitude of 1 unit then realized energy is changed about 32 times.

So a magnitude-32 starquake (recorded neutron star explosion – December 27, 2004) would be about 580,000,000,000,000,000,000,000,000,000,000 more powerful than the earthquake of M1.0. The visible recorded sunquake on July 9, 1996, had a Richter magnitude of 11.3, which means that this seismic event on the Sun, was about 30,000 times more powerful than the Turkish earthquake on February 6, 2023 (M7.8).

Physical considerations

Magnitude determination

During the early thirties of the 20th century, Charles Francis Richter from Caltech inspired by the stars' magnitude based on the intensity of light emission (Figure 1) developed the magnitude scale of earthquakes to assess the power of the seismic events, based on the seismograph records of seismic waves. Some years later together with Beno Gutenberg created the first calibration function's tables to increase the accuracy of the magnitude assessment of far-field earthquakes, using the surface waves as the main carrier of seismic energy [8] – (Figure 2).

The determination of the magnitude of a single earthquake is based on the dependence of the amplitude of different types of seismic waves, recorded on the seismogram is presented in Figure 3.

As seen by the pictures and definitions, the birth of the Richter magnitude scale is based on mathematical assumptions and the definitions presented earlier (see paragraph Definitions). The logarithmic scale seems to be useful for such investigations because it covers a very wide dynamic range. The experience on the Earth shows well consistent energy spreading and the ability to compare different types of seismic events' energy (Figure 3).

Sunquakes properties

Many investigations mentioned the different properties of the sunquakes and a summary of seismic surface waves shows:

- The surface waves propagate over similar distances (approximately 10 Mm - about 10 diameters of Earth, depending on the power of the sunquake).
- The accelerations for these investigated cases [4] range between 0.011–0.020 km/s^2,

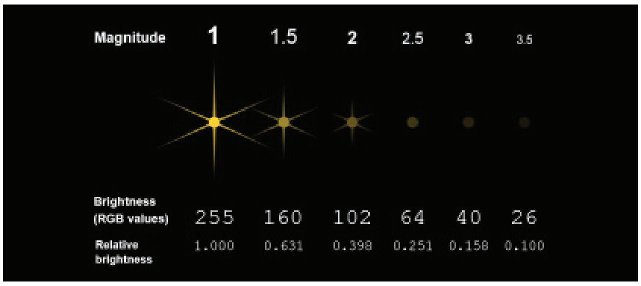

Figure 1: Star magnitude's scale according to brightness [18].

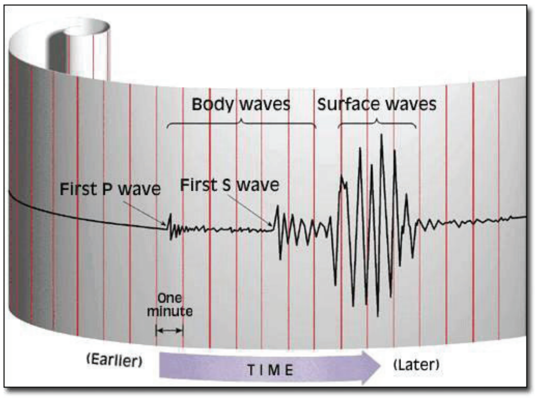

Figure 2: Earthquake seismogram with main types of seismic waves [20].

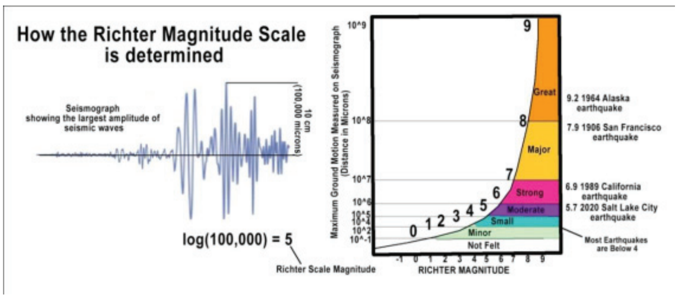

Figure 3: Determination of the power of earthquakes and comparison of the different seismic events [20].

- The travel times of the observed surface waves are between 30 and 60 min traveling until they dissipate to the level of microseismic noise of the Sun with accelerated velocity from tens km/s to about hundreds of km/s.
- The frequency of the surface waves of sunquakes varied but were in the range of 2 mHz to 6 mHz (3 mHz for the event of 1996).
- The diapason of magnitudes varies between 8-9 magnitude units to 13-15 units for the sunquakes, supported by 9 "visible" sunquake signatures measured during the 24th Sun activity cycle) [4].

As mentioned earlier a case study of a sunquake on July 9, 1996, produced visible surface waves in the photosphere of the sun – (Figure 4). The transformation of the seismic energy carried by the waves obtained the "Richter-Gutenberg" magnitude of 11.3 [3].

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Later on John T. Stefan and Alexander G. Kosovichev, 2020 [6] "tested two types of excitation mechanisms: an instantaneous transfer of momentum to the surrounding atmosphere—analogous to the shock excited by the thermalization of the electron beam—and a more gradual transfer of energy modeled as an applied external force."

Estimating the source of sunquakes with a model of high-energy electron rays and considering the magnetic field dumping to the surface waves [5] thus the energy of the excitation mechanism permits reaching the following parameters for Momentum Mechanism – MM and Force Mechanism-FM for several observed sunquakes and the models by the authors:

Energy (MM) – 10^{27}-10^{32} [erg] (10^{20} – 10^{25}) Joules;

Energy (FM) - 10^{27}-10^{29} [erg] (10^{20}-10^{22}) Joules;

Velocity (MM) – from 11km/s to over 2800 km/s

Using this analogy and the transformation formulas it is easy to transform the sunquake magnitudes into energy and vice versa. The extensive research of the 24^{th} (2011-2017) solar cycle by Ivan N. Sharykin and Alexander G. Kosovichev 2020 [5] shows numerous sunquakes with the energy budget of the investigated events varied between $0.5 x 10^{26}$ to about 60 x 10^{26} erg ($0.5 x 10^{19}$ to $60 x 10^{19}$ Joules). This gives the possibility to assess the diapason of the magnitudes 9.7 to 11.6 using the formula Es-Me. Extrapolating the upper limit by factor 3-3.5 (the sun is 333 times bigger than the Earth and the maximum energetic sunquakes are not yet observed), then the maximum expected magnitude could be 14.6-15.0. This is with the agreement with independently assessed lower boundary based on the microseismic noise on the surface of the Sun.

These calculations are agreed upon by the following considerations:

The size of the granules at the top of the solar cells varies between 100 km to 1000 km – (Figure 5). Making an analogy with earthquakes the surface cracks on the earth with similar seismic events' sizes can generate earthquakes with magnitudes between 7.0 and 9.0 Richter scale. This means that seismic events with similar magnitudes cannot be observed on the Sun's surface because their waves' amplitudes will be less than the amplitudes of the solar microseismic noise and cannot be recognized on the photo pictures as separate sunquakes.

This gives a possibility to assess the lowest seismic event magnitude equivalent to the earthquake. The lowest magnitude event is limited by the 100 km to 1000 km cells existing for about half an hour. This means that it could be equivalent to the magnitude 7 to 8 earthquake because if it is less it will be compatible with the cells' size and lost in the background of the microseismic noise of the Sun. So, the lower limit of the sunquakes can be established at a level of M7-8 earthquake.

Main parameters of fluid stars

The general classification of the stars is presented by the H-R (Hertzsprung-Russell) diagram (Figure 6). It gives the relationship between thew surface temperature of the stars and their luminosity in solar units. In general, the variance of parameters according to the Sun's properties is as follows:

- Surface Temperature: 3000K-50000K;
- Luminosity: 10^{-5}Lo - 10^{6}Lo;
- Radius: 0.01Ro - 800Ro;
- Mass: 0.08Mo - 80Mo.

There are several modifications of this diagram, including magnitude, radius of the stars, their spectral classes, etc. (Figures 7,8). These modifications are very useful for the interpolations assessing stellarquakes magnitudes and the diapason of their variance.

What is important to mention as well is that the change in the magnitude ΔM of stars can be calculated by the equation:

$$\Delta M = -\frac{5}{2}\log_{10}[\frac{I}{I_0}] \quad (5)$$

or ΔM = 2.5 log(Io/I) or m = -2.5 * log10(I), (6)

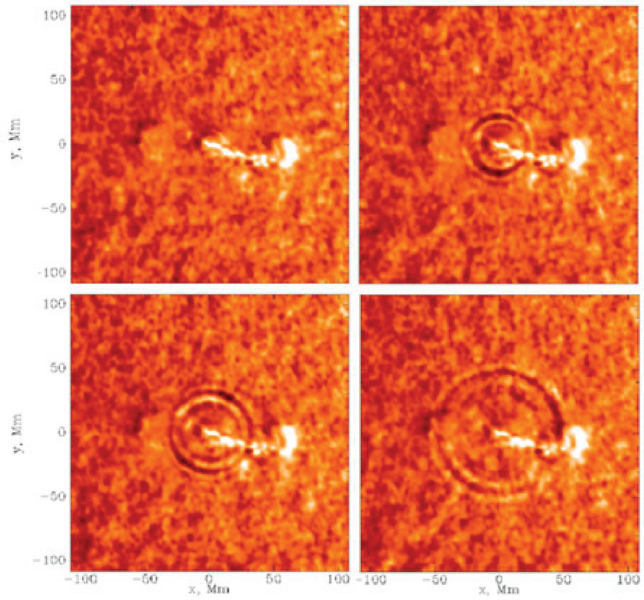

Figure 4: Surface waves on the Sun's surface generated by the protuberance of July 9, 1996, as pictured by the Solar and Heliospheric Observatory (SOHO) mission [21].

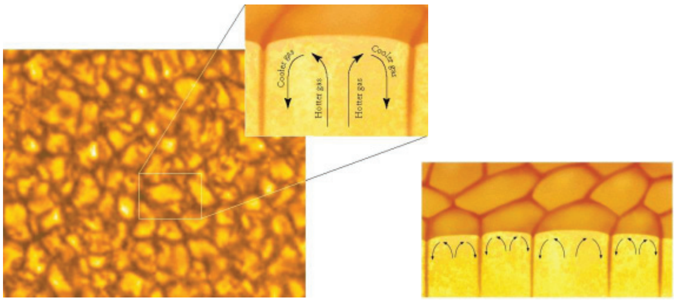

Figure 5: Close-up Picture of the Photosphere and size of the solar granules [17].

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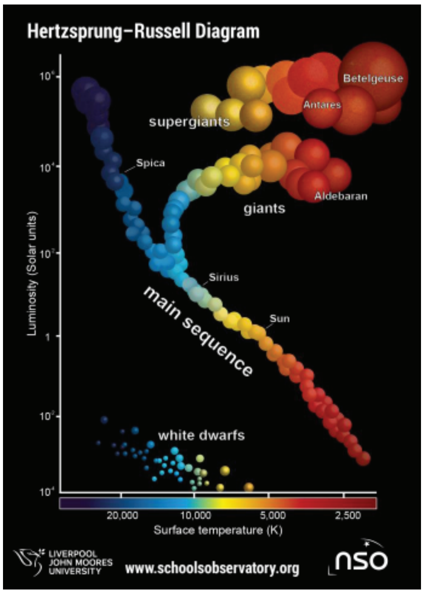

Figure 6: H-R diagram of luminosity depending on spectral temperature [22].

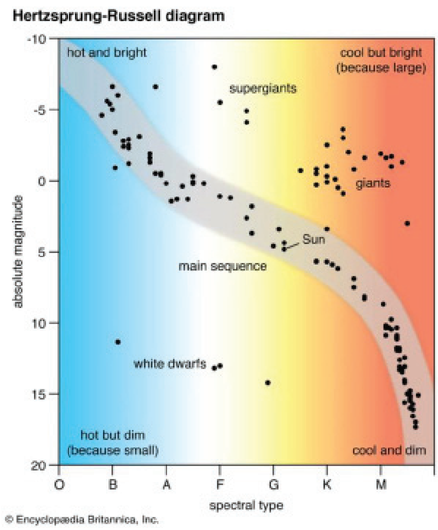

Figure 7: H-R diagram of the absolute magnitude of stars [23].

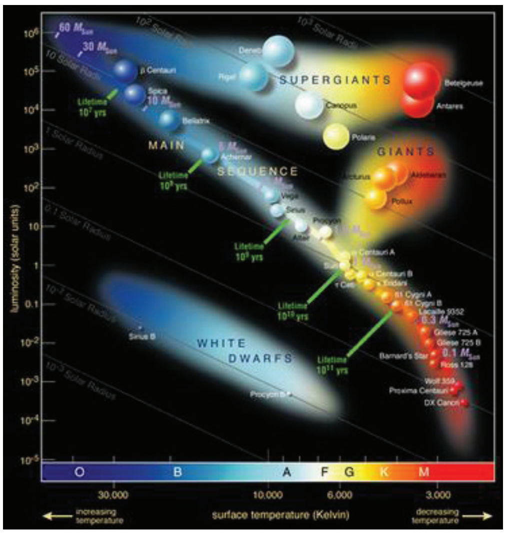

Figure 8: Luminosity (in solar units) temperature and spectral classes and the solar radius outlining the typology of stars (some of them named) [24].

where I is the intensity of the star with familiar magnitude M, and I_0 is the intensity of the object whose magnitude is searched. This formula is an independent confirmation that the log scale can be used for the purposes of this investigation [24].

The specifics are related to the temperature and mass. The most massive stars are located in the left upper corner and the smallest and relatively cooler – in the right low corner of the diagram. The importance of this diagram in relation to the magnitude assessment is due to the possibility of stars accumulating stellarquake potential, which increases from right to left and from down to the top. On the other hand, this is also important to assess the magnitude estimated accuracy. The accuracy is higher at the bottom part of the diagram and decreases going up. The important issue is that all assessments are based on surface wave magnitudes calibrated to the Sunquakes.

Assumptions

The main assumptions accepted for this study are:

- The magnitude assessment of stellarquakes on fluid stars is based only on the surface seismic waves.
- The assessment by this magnitude scale does not include the energy budget produced by all other possible energy-emitting sources of a fluid star (for example such as gamma and X-rays, plasma flares, magnetic perturbations, etc.).
- The fluid in which the surface waves propagate is considered homogeneous.
- The sunquakes are the main calibrating factor because their magnitude is assessed by direct measurements. For example, a moderate-sized flare on July 9, 1996, produced a sunquake measured as magnitude 11.3 on the Richter scale.
- The generation potential of the fluid stars is accepted proportional to their radius.

Methodology

The methodology of stellarquake magnitudes assessment is based on several basic principles:

- Following the properties of the fluid star (Figure 9), the linear extrapolation and interpolation are considered representative enough for the assessment of the magnitudes of the stellarquakes. This is confirmed by many investigations and results of the sunquakes' energy emitted and carried out by the seismic surface waves of the sunquakes.
- Of course, the internal structure and composition of different types of fluid stars vary greatly, and the simple analogy method of using linear extrapolation and interpolation to evaluate the seismic magnitude of stars may not accurately reflect complex physical processes. This is only a technical simplification that offers the

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possibility to transform seismic energy to magnitude units and vice versa.

- The typology of the stars permits the assumption of the stellarquakes power potential to be proportional to the stellar sizes (radius), masses, temperatures, and position on the Hertzsprung-Russell diagram. It gives the possibility to assess the stellarquake magnitude for the spectral classes O-M (of the main sequence). The Giants, supergiants, and white dwarfs need a similar approach but for each group separately – (Figures 9,10).
- The dominant number of stellar masses is about 90% in the mass interval of 0.25 to 2 Sun masses. This means that the focus of our investigation is important to be on the right part of the H-R diagram which contains a larger number of the fluid stars (Figure 10).

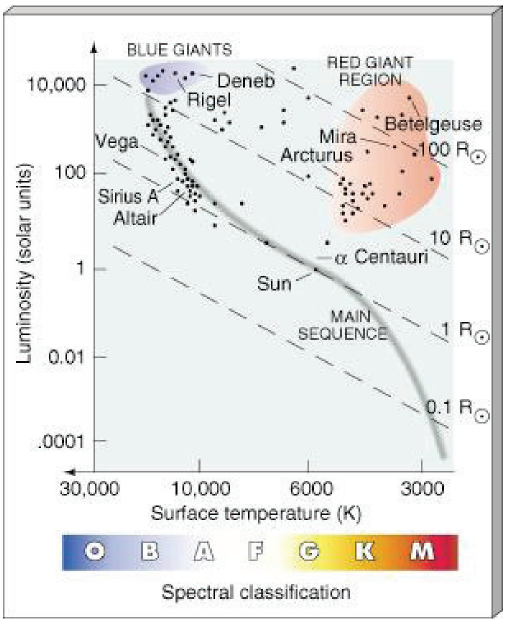

Figure 9: H-R diagram with the Sun's radius dependence and main sequence of stars. Blue and Red supergiant regions are outlined [25].

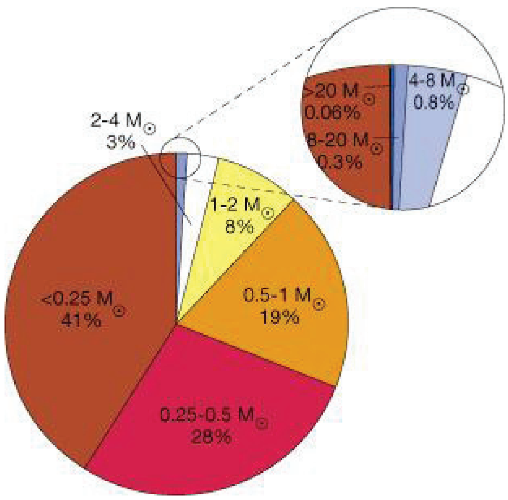

Figure 10: A diagram showing the stellar masses distribution according to the Sun mass [25].

- Usage of the approach of Richter-Gutenberg for the earthquake magnitude assessment by surface waves (i.e. logarithmic scale) for large dynamic diapason performed on stellarquakes.
- Sun calibration for all stellarquakes as the sunquakes are better investigated and have enough statistical weight to be considered reliable
- Independent assessment of the upper and lower limits of possible stellarquakes, proved by independent methods (especially for the sunquakes) and extrapolated to the other stars' spectral classes.

Such a methodological approach provides a common integrated view of the assessment of stellarquakes magnitudes and the diapason of their variations. This could be very useful for the observational planning of different missions targeted to study the phenomena called stellarquakes.

Results and comparative analysis

Using the described methodology and considering mathematical and physical assumptions the magnitude intervals of stellarquakes are estimated, calibrating all magnitudes are determined transforming magnitudes in seismic energy and vice-versa. A similar approach is performed for all spectral classes' stellar objects classified by the H-R diagram (excluding neutron/pulsar/magnetar/ compact stars). As mentioned earlier the generation mechanism of stellarquakes is disputable, but most scientists consider the source of an explosion inside the star substance as a source of stellarquake.

In this investigation, the generation mechanism of stellarquakes is not under consideration. Only the surface seismic waves are considered and magnitudes are calculated by their parameters. As proven earlier, the logarithmic scale could be representative of comparing the assessed stellarquake magnitudes (Figure 11). To be able to present visually the assessment done, a table has been created, (Table 1). It offers a possibility to draw schema about the stellarquakes magnitudes and the diapasons of their variations. Due to the high uncertainties, the hypothetic Mmax and Mmin have larger value variations, as well. The uncertainties and variations of the magnitude diapasons are due to the energy budget of the emissions by stars of different temperatures and masses. Low limits of uncertainties are determined more or less by the upper limits of other classes in the classifications. The upper limits are also considered dependent on the above-mentioned parameters, but their variance is much larger due to the possible flares the maximum of which is possibly not yet observed and detected.

The general issues extracted from the obtained results are as follows:

- Application of the described methodology gives a possibility to assess the expected hypothetical stellarquakes magnitude and to make a comparison

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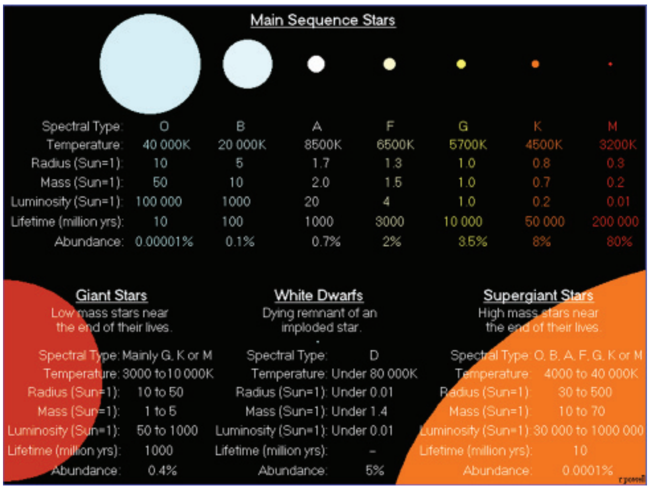

Figure 11: Comparative picture of the stars' parameters and appearance of the different typology classes.

Table 1: Approximate hypothetical average magnitude assessment of stellarquakes and expected DIAPASON DETERMINED on the dependence of the types of fluid stars according to Hertzsprung-Russel diagram and "Richter's" magnitude of surface waves.

Spectral Class	Average magnitude	Magnitude max	Magnitude min	Diapason	Type of stars
A-K	9,7-11.7	14.6-15.0	7.0-9.0	8 units	Main sequence
K-M	9.0-10.0	10.5-11.5	6.0-6.5	4.5 units	Main sequence R
O-A	10.0-12.0	15.0-17.5	7.5-8.5	10 units	Main sequence L
G-M	12.0-14.0	14.0-15.0	9,5-10.5	5.5 units	Giants
G-M	18.0-20.0	20.0-25.0	17.0-18.0	8 units	Red Supergiants
B-A	18.0-20.0	20.0-25.0	17.0-18.0	8 units	Blue Supergiants
B-G	8.5-9.5	10.0-10.5	6.0-6.5	4.5 units	White dwarfs

Legend: A-K is part of the main sequence (Sun and similar); K-M is a part of the main sequence: (R) located to the right of A-K (low masses and temperatures), O-A is a part of the main sequence (L) - located to the left of A-K (high masses and temperatures).

between the different spectral classes of the fluid stars and their stellarquake potentials. The reliability of such an approach is disputable, of course, but it is better to have such a tool than to try to assess each separate seismic event on a fluid star registered by the observation missions.

- The accumulation of enough statistics could be useful for the corrections of the results obtained. It is phenomenologically clear that the sizes of stars are influencing the magnitude assessment in a wider diapason.

- For group A-K, it is easier to assess the hypothetical stellarquake magnitudes. The gradient on the graphic is lower for the main sequence for A-K. The similarity of this group to the Sun makes more reliable the assessment of stellarquakes magnitudes. For the K-M group, the gradient is higher but the low mass and radius make the assessment more accurate. The O-A group looks much more energetic and is easy to accept higher average magnitude and higher dispersion.

- In the G-M group (giants), the variation of average stellar magnitude is smaller. The giants lie on almost a straight line and have relatively low temperatures, which made them with lower stellarquake potential. The same is valid for group B-G (white dwarfs) because of their small masses.

- The most difficult is the magnitude assessment for stellarquakes of the supergiants. They are separated into two groups - groups G-M (red supergiants) and B-A (blue supergiants). Both are dispersed on the HR diagram and have larger potential due to their masses (to the right part of the diagram) and very high temperatures (located on the left part of the diagram). Thus their magnitude assessment is most difficult due to their sizes and temperature variations.

To be able to visualize our results a comparative scheme is presented in Figure 12.

For the visualization of the different fluid stars' groups and their magnitude assessment, a scheme is plotted again on the H-R diagram – Figure 12. This is just a visual representation with no exact scale of M on it. The exact numbers of the magnitudes' diapason and uncertainties of magnitude assessment are in Table 1 and Figure 13.

What can be extracted by the stellarquakes' magnitudes of the stars from the Main Sequence? They have approximately the same changes for most spectral classes. Exclusion is the stars on the right low corner which have small masses and low temperatures (red and brown dwarfs). Their magnitude

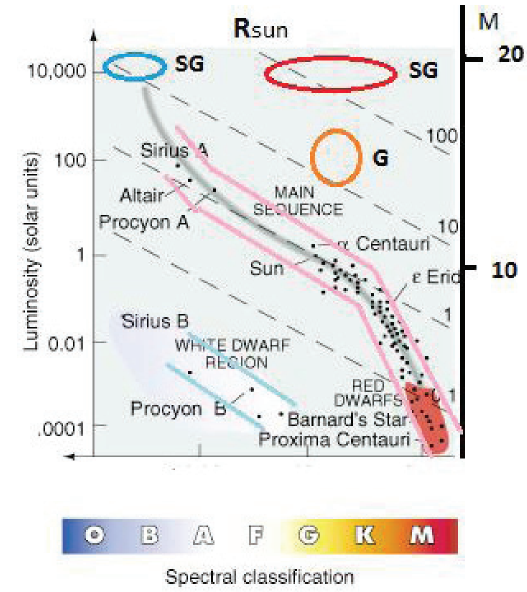

Figure 12: Schema of H-R diagram with possible magnitude assessment about all types of fluid stars. Magenta – for the Main sequence; brown – for the group of giants; blue – for the group of white dwarfs; red – for the red supergiants; dark blue – for the blue supergiants. Red dwarfs are not separated. The numbers about magnitudes' diapason and uncertainties of magnitude assessment are in Table 1 [23] modified by B Ranguelov.

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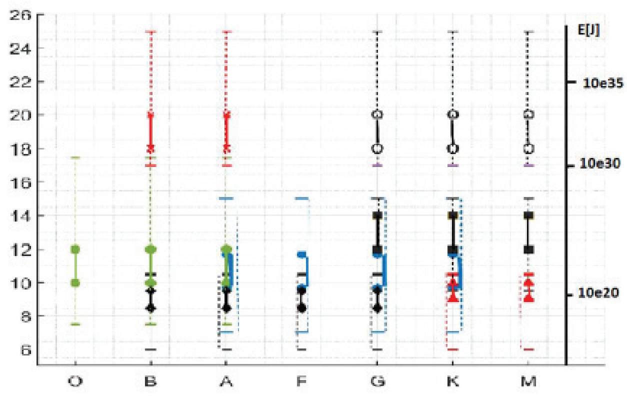

Figure 13: Seismic energy, magnitude diapason (solid lines), and uncertainties (dashed lines and horizontal bars) *vs*. spectral classes (O-M) for: Main sequence - green and blue dots and red triangles. White dwarfs – black diamonds. Giants – black quadrats. Blue supergiants – red crosses. Red supergiants – black circles.

variations are smaller and even closer by magnitudes to the solid planets of the Solar system. The magnitudes' variations related to the Giants and Supergiants, are in the narrow band where the magnitude has similar values and the dispersion of accuracy increases from down to the top. (Figure 13). There is also a publication about a brown dwarf stellarquake, mentioned as the smallest stellarquake [26,27] with a power of 14% of minimal sunquake registered.

Finally, we did a loop from the magnitude (brightness) of stars scale to the earthquake magnitude scale on earthquakes and back to the stellarquakes magnitude scale.

Conclusion

A methodology for stellarquakes magnitude assessment was developed using the basics of magnitude determination of earthquakes. The extrapolation procedure was applied to extend the coverage to stellarquakes' magnitudes on fluid stars by the method of surface seismic waves' power. The H-R diagram was used and the assumption of magnitude-size-class of stellarquakes to assess the hypothetical average expected stellarquakes magnitude, as well as the possible variations about the accuracy of assessment, were performed.

The practical table and a figure expressing these dependencies are produced. They can be useful in the planning of space missions targeted to the stellarquakes' registration and observations.

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